(NASA-CR-142022) RADIATION MEASUREMENTS FROM POLAR AND GEOSYNCHRONOUS SATELLITES Annual Report, 1 Oct. 1973 - 30 Sep. 1974 (Colorado State Univ.) 38 p HC $3.75 CSCL 04B G3/47
N75-16183
Unclas
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RADIATION MEASUREMENTS FROM POLAR AND GEOSYNCHRONOUS SATELLITES

T.H. VONDER HAAR, PRINCIPAL INVESTIGATOR



ANNUAL REPORT

GRANT NGR-06-002-102

(PERIOD: 1 October 1973 - 30 September 1974)



DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

RADIATION MEASUREMENTS FROM POLAR AND GEOSYNCHRONOUS SATELLITES

Annual Report

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Grant NGR 06-002-102

(Period: 1 October 1973 - 30 September 1974)

by

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Department of Atmospheric Science
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December, 1974

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SUMMARY

The fourth year of grant sponsorship emphasized the use of newer satellite data from Nimbus 5 and an extension of studies initiated with earlier satellite data. We have begun climate studies using satellite data to guide climate model experiments. The delayed launch of ATS-F and its short-lived Very High Resolution Radiometer (VHRR) limited its research usefulness during this reporting period. The areas of application of satellite data continue to be primarily:

a) a physical basis for an understanding of the long-range (short-term climate) and climate monitoring and prediction problem;

b) delineating energy loss to space between contributions from land, ocean and atmosphere;

c) temporal and spatial distribution in earth's energy budget and its variations due to global cloud fields; and

d) studies of the frequency of occurrence of precipitation over ocean areas.

The above areas of data application to very complex problems are closely related to longrange objectives of the Global Atmospheric Research Program (GARP) and more specifically to the Radiation Subprogramme of GARP Atlantic Tropical Experiment (GATE) and to the Study of the Physical Basis for Climate Change ("GARP-2").

This period has seen much interaction with other scientific groups to identify problems involved in short-term and long-term climate monitoring and prediction. The design of new satellite experiments to continue monitoring the earth's radiation budget with improved relative

accuracy have developed from such interactions. Earlier data from first and second generation satellites (TIROS, Nimbus, etc.) aided in establishing the design and measurement criteria for future satellite systems.

1.0 INTRODUCTION

For the October 1973 to September 1974 period research continued on studies initiated during previous reporting periods along with a new study on global precipitation patterns using satellite data. Five areas of research emphasis are discussed in the next section.

The grant has fully supported M.S. candidate S. Kidder, Ph.D. candidate J. Ellis and several other research associates. In addition several scientific papers were presented at international and national gatherings. A cumulative summary of all reports and publications produced under this grant appears in the Appendix B. The principal investigator was an invited participant at the Stockholm Conference on the Physical Basis of Climate and Climate Modelling (August, 1974). He participated in the working group on satellite observations of climate parameters and interacted with modelling, oceanographic and polar working groups.

2.0 DISCUSSION OF SCIENTIFIC RESULTS

2.1 Interannual Variations of the Earth's Radiation Budget and Atmospheric Response; Relation to Short Term Climate

Year-to year variations in the north-to-south gradient of net radiation and related variations in the general circulation of the atmosphere continue to be a focal point for our climate study. The objective has been to determine a physical basis for observed anomalies.

The effort to date has been to examine various semi-empirical climate models for an experiment. Climate models in our possession which execute on the CSU CDC 6400 computer are models by Budyko, Sellers, Leith-Budyko, and time dependent versions of Budyko's, Sellers', Stone's

and Faegre's (Schneider and Gal-Chen, 1973). Additionally we have been investigating Julian Adem's long-range forecast model as a tool for studying interannual changes in weather and radiation budget.

None of the aforementioned models allow for cloud feedback, i.e., clouds are specified as climatic mean values. Efforts here are directed to improving radiative transfer parameterization in semi-empirical climate models. Cloudiness at various levels and of various types can then be injected into the models in specified latitude zones to test climate model response in terms of, say, north-to-south midtropospheric temperature gradient, thermal wind, etc. Model sensitivity tests to semi-permanent changes in cloudiness may advance an understanding of cloudiness-climate relationships and further an understanding of cloud feedback.

Leith (1974) showed how Budyko's semi-empirical climate model (1969) could be modified to use satellite measured earth-atmosphere zonally averaged radiant exitance to space and albedo. Essentially, the model can be expressed in terms of a parameterization between horizontal flux divergence, $D(\theta)$, and north-to-south infrared radiant exitance profile, $I(\theta)-\bar{I}$:

$$D(\theta) = \beta(I(\theta)-\bar{I})$$

where β is a constant and $\bar{I}$ is hemisphere average infrared radiant exitance with an assumption of radiative balance.

Leith (1974) pointed out that a singled value β is questionable. Ellis and Vonder Haar (1974) show the constant, β, should be a function of latitude, $\beta(\theta)$. Figure 1 shows that β varies with latitude

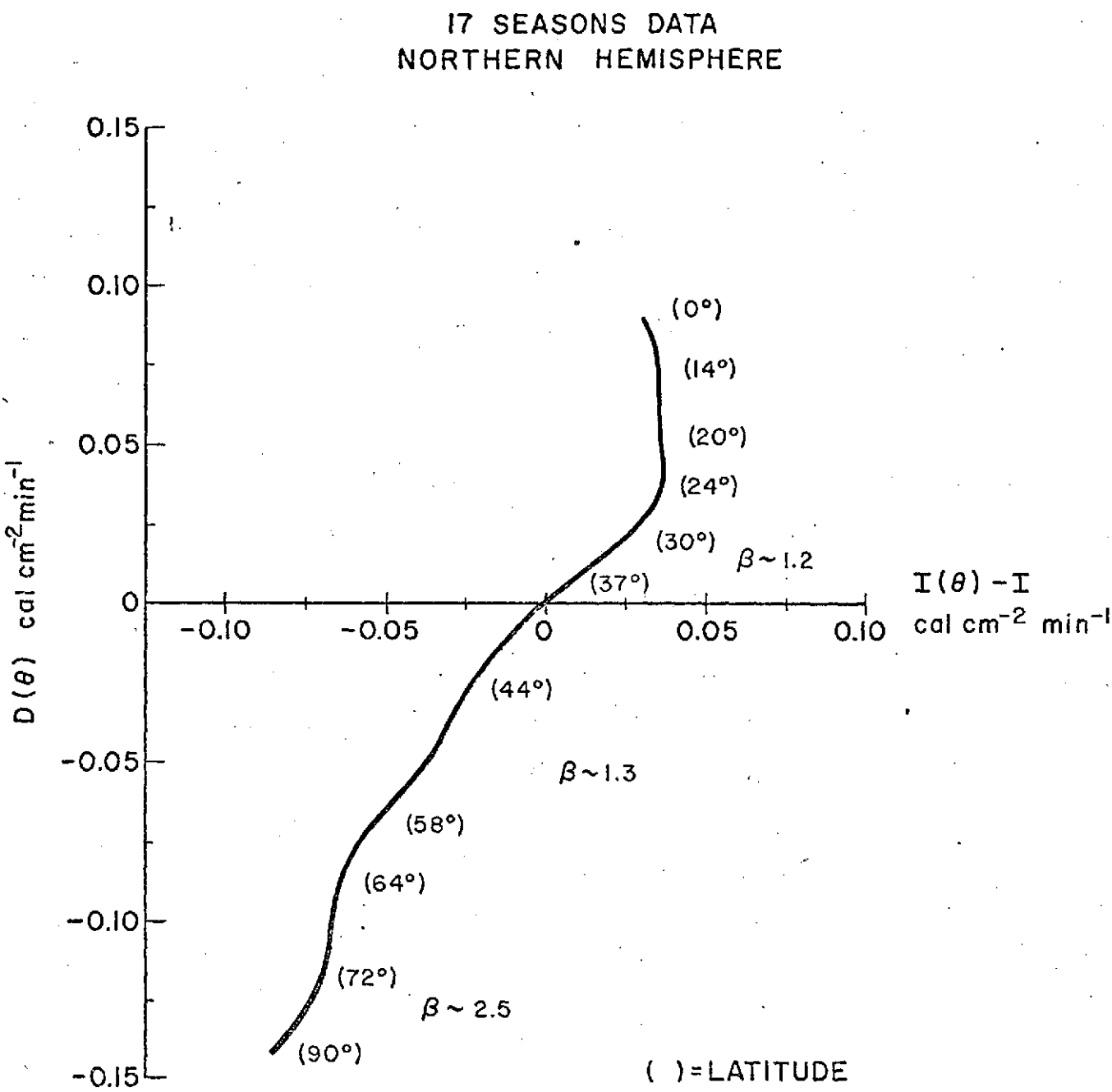


Figure 1. Functional relationship between zonal averaged horizontal flux divergence [D(θ)] for atmosphere, ocean, land, cryosphere system and the zonal averaged infrared radiant existance derived from 17 seasons satellite data.

from approximately 1.3 $cal \cdot cm^{-2} \cdot min^{-1}$ to infinity. Budyko's model used a value for β of 2.61. The updated model shows that constant β seems to be an oversimplification of the problem.

As Leith (1974) did previously, we selected a β equal to 1.61 as being a somewhat better representation for the parameterization. Budyko (1969) suggests that a 1.6% reduction in the solar constant is sufficient for an ice covered northern hemisphere. Our results, using the 17 seasons satellite data set, suggests that a decrease in the solar constant of greater than 5% (σ/σ_p) is necessary for the model to become unstable. Our results are shown in Figure 2; curves labeled RN and RS show the latitudinal movement of the ice boundary with a reduction in solar constant for the northern and southern hemispheres, respectively. Numbers on the curves represent mean latitudes of the ice-snow boundary for model initialization; vertical hacks on curves show points where model instability is reached.

It is apparent that a more sophisticated model than Budyko's should be used for our study. A time-dependent version of Sellers' zonal symmetric model (Schneider and Gal-Chen, 1974) and a two-dimensional model of Julian Adem (1968) are being implemented.

Studies have also been completed which examined interannual variations in the north-to-south gradients of infrared radiant exitance and column absorption. Winston (1967) found that the maximum gradient of longwave radiation in five day periods correlated well and positively with maximums in 800 to 500 mb zonal wind speed. On an interannual basis we did not find a good correlation between north-to-south gradients of either infrared radient exitance or reflected radiation

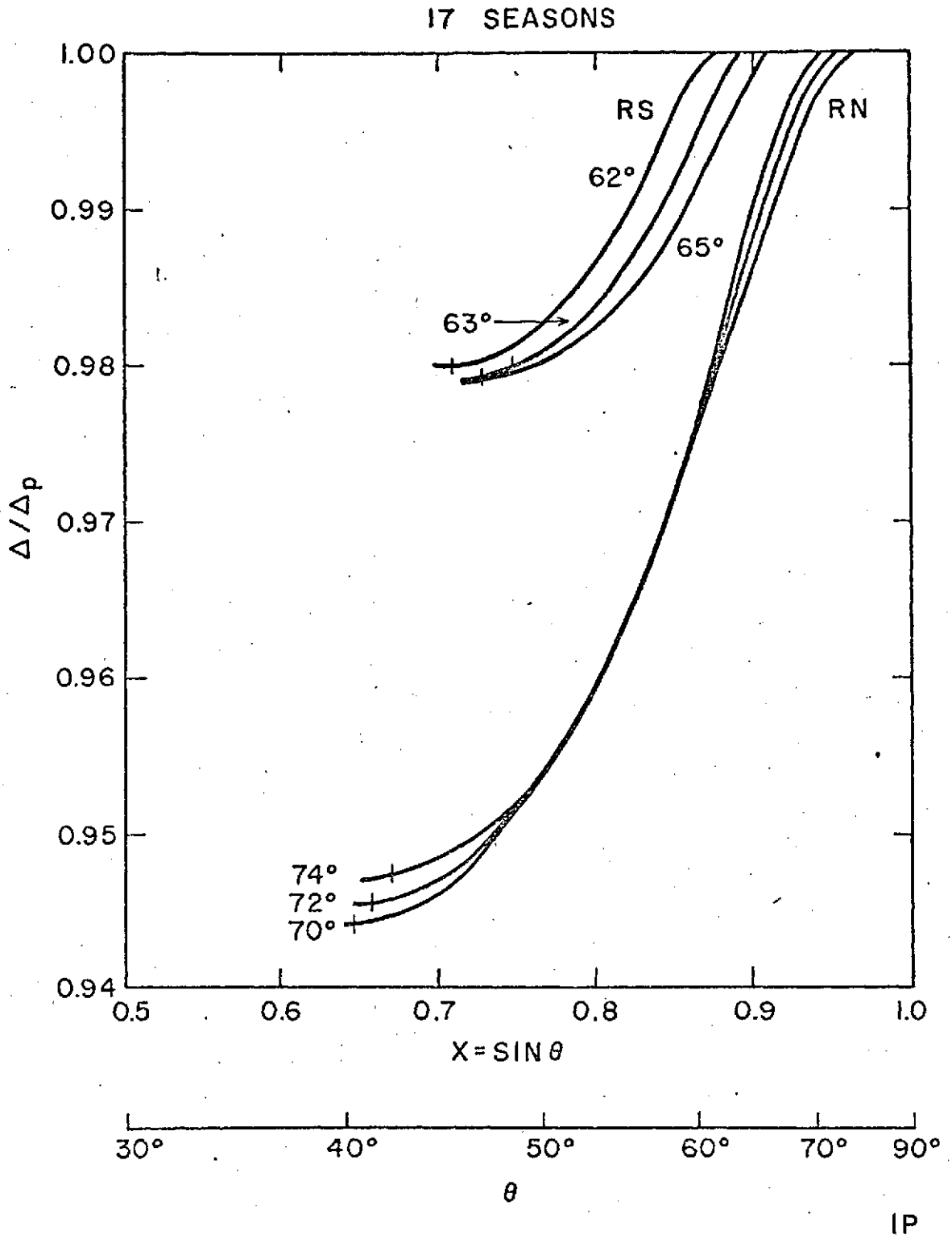


Figure 2. Budyko-Leith climate model generated ice-snow boundary latitudes for various reductions in the solar constant ($\Delta/\Delta p$) using 17 seasons satellite data. Vertical hacks indicate latitude for model instability RN: northern hemisphere, RS: southern hemisphere.

and general circulation parameters. Figure 3 shows time lag correlation coefficients with the gradient of infrared radiant exitance. In general the coefficient is 0.50 or less at all lags for the various circulation parameters; none are statistically significant.

Figures 4 and 5 show magnitude in the year-to-year variations of the gradient of infrared radiant exitance ($\Delta RL'$) and reflected radiation ($\Delta RR'$); gradient anomalies range from zero to 0.04 $cal \cdot cm^{-2} \cdot min^{-1}$ (28 watts m^{-2}). Values above 0.01 $cal \cdot cm^{-2} \cdot min^{-1}$ are greater than the estimated systematic bias of 5% (Ellis, 1972) in each satellite data set so that 65% of the values in Figure 4 and 38% of the values in Figure 5 are above "noise". Thus, one would expect these anomalies to be a real phenomena.

2.2 Earth's Surface Albedo Using Satellite Data

Minimum albedo data derived from data taken with a medium resolution infrared radiometer (0.2 to 4.8 μm spectral band) on Nimbus 3 satellite are now available for 10 semimonthly periods. They are in the form of pole-to-pole zonal averages, global and continental area maps.

These data are now being used in research efforts at UCLA, Goddard Institute for Space Studies, NOAA, and the Division of Atmospheric Physics (CSIRO), Australia. They are also being applied to climate model experiments here at CSU as reported in Section 2.1.

Minimum albedo is the smallest observed albedo at each grid area over a semi-monthly period (approximately 1 to 15 days). These data are a first order approximation to the earth's surface albedo. Variations in atmospheric transmission due to absorption, molecular and particle scattering, and some residual cloudiness suggests that minimum albedo measured from satellites is not precisely the earth's surface albedo.

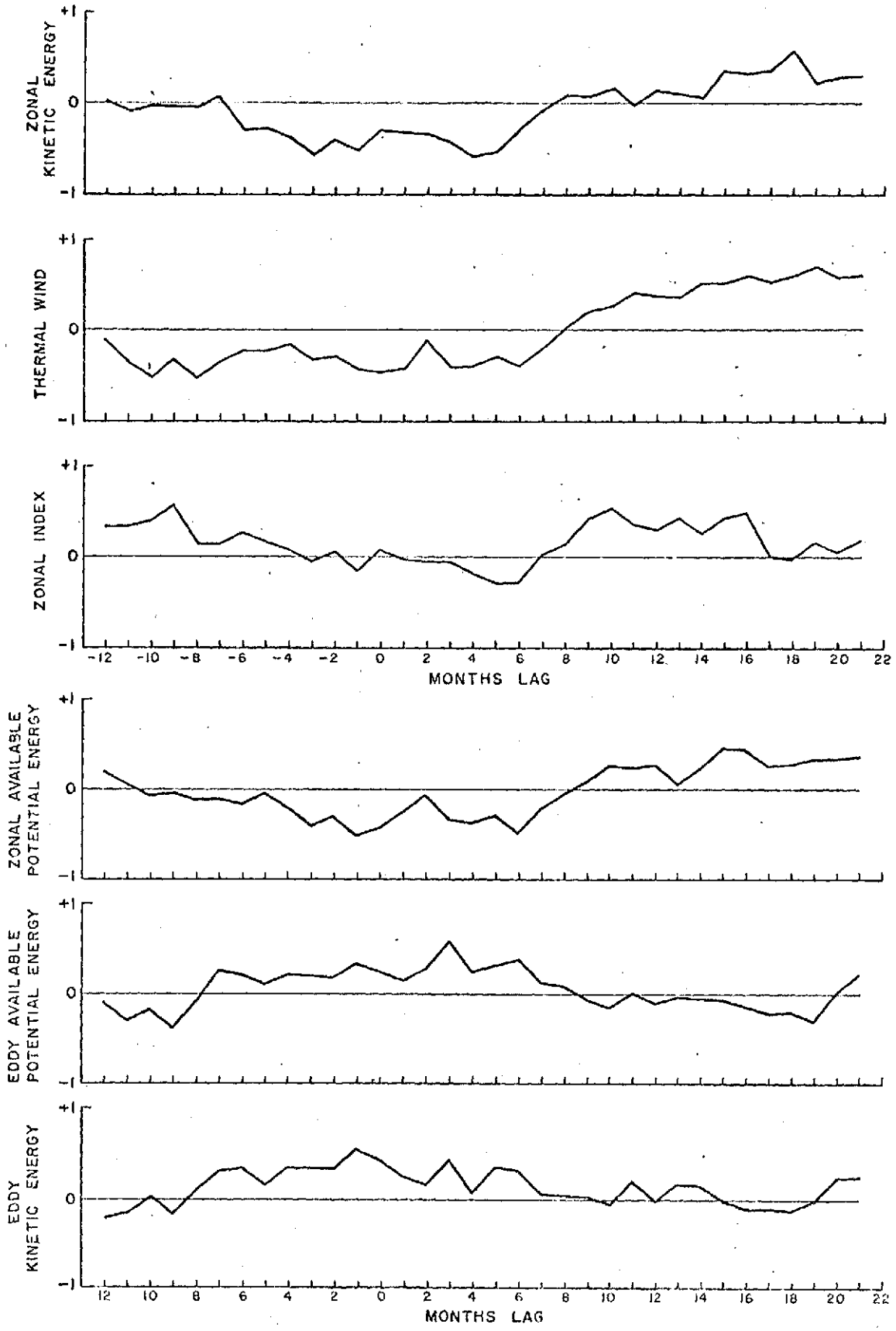


Figure 3. Lag correlation coefficients between interannual variations in general circulation parameters (GP') and north-south gradient of infrared radiant exitance (ΔRL'); - months (+ months) for GP' leading (lagging) ΔRL'.

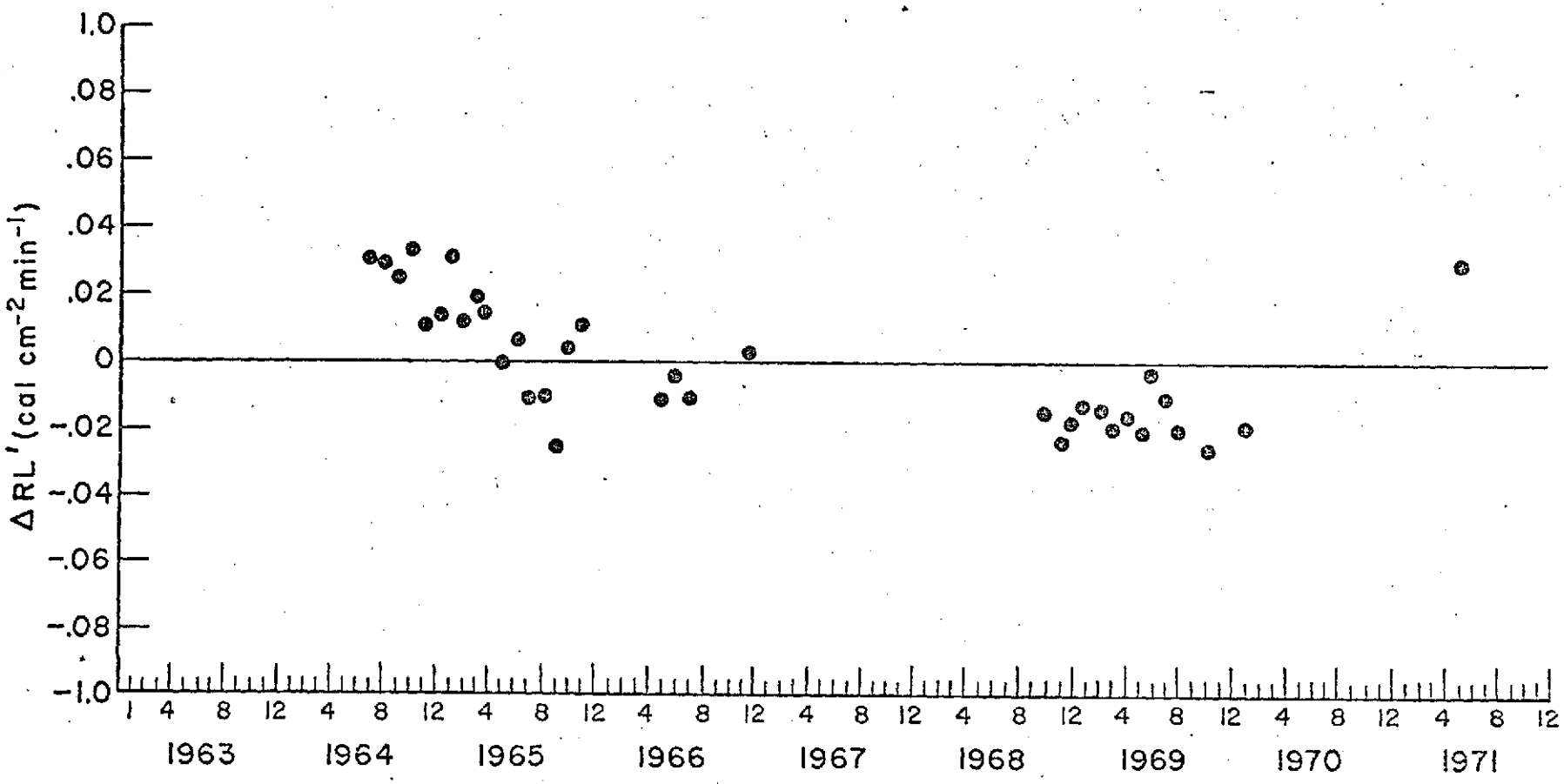


Figure 4. Temporal distribution of the infrared radiant exitance gradient between latitudes 65 to 5 North with annual cycle removal (ΔRL')

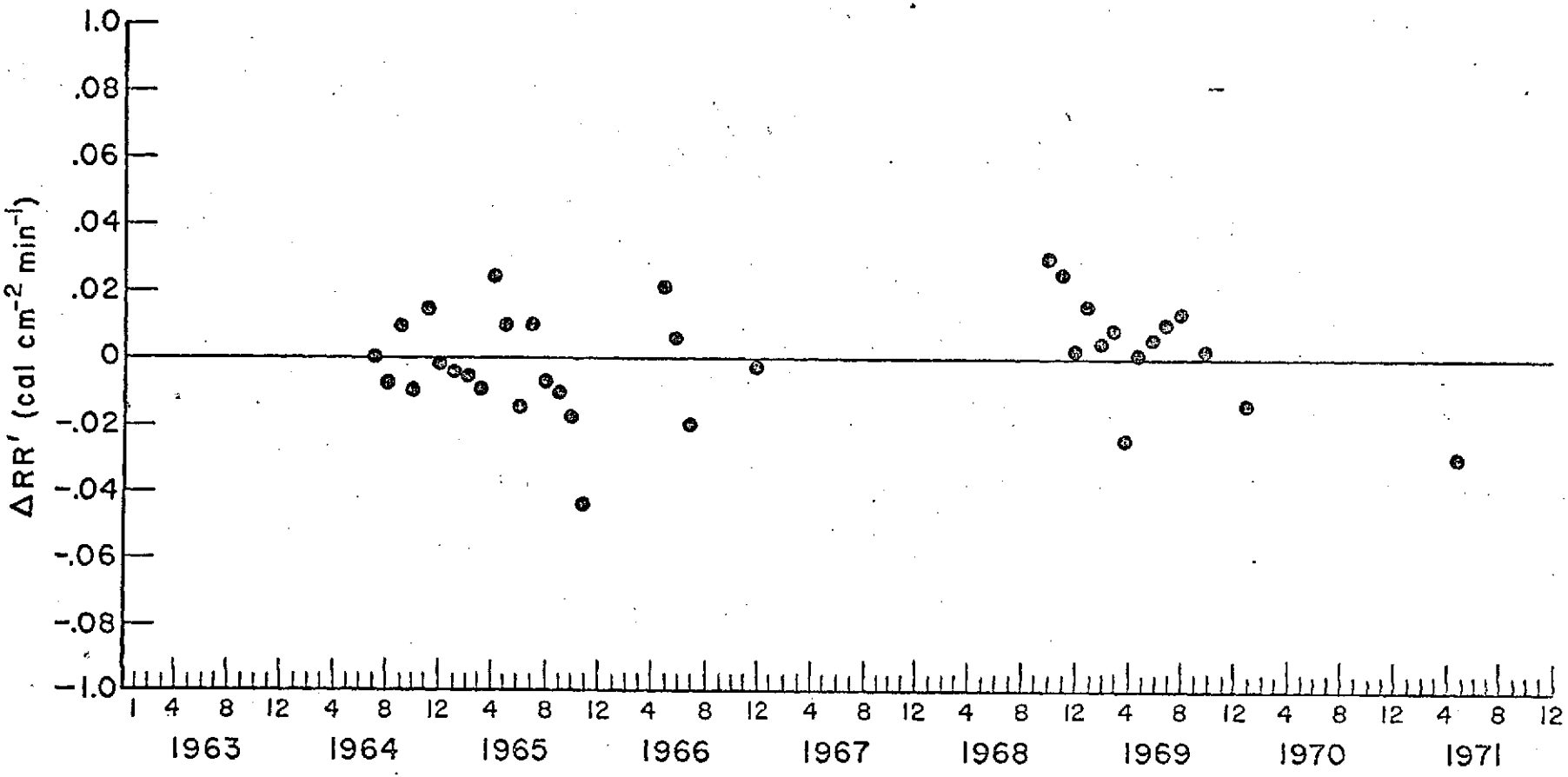


Figure 5. Temporal distribution of the radiation reflected to space gradient between latitudes 65 to 5 North with annual cycle removed (ΔRR')

Minumum albedo data have been stratified into various groups representing different types of vegetation and then compared to earlier aircraft measurements of Kung et al. (1964). This comparison for North America is shown in Table 1 where their work is enclosed in parenthesis and snow covered surface is indicated with an asterisk. For snow free surfaces the two different albedo sets are in good agreement. There appears to be a tendency for the minimum albedo data to be systematically higher, i.e., broadleaf deciduous forest, prairie and steppe are nomally 1 to 2% higher and desert is 2 to 3% higher.

The reduction of Nimbus 3 radiance data to albedo values implemented a bidirectional model to account for angular differences in reflection over various backgrounds (Raschke et al., 1973). Data of Kung et al. (1964) were taken with a Kepp and Zonen Solarimeter with a 4^{o} focused beam width. At their 300 meter flying altitude this instrument saw approximately 21 meters at the earth's surface. Albedo over various types of vegetation and terrain were measured. Their data reduction did not account for angular reflection; they assumed isotropy. Model experiments show that reflections, integrated over various solar azimuth and zenith angles as observed by a satellite fixed in space, differs by as much as 3 to 6% in middle latitudes, depending on whether a diffuse assumption is made or a bidirectional reflectance model is used in data reduction (Vonder Haar and Campbell, 1974). Of course, the model experiment did include cloudiness where upon if cloudiness were removed the directional dependence of the reflection may not be so severe. The difference between minimum albedo and aircraft surface albedo results are of the same size as the difference between assuming isotropy and applying a bi-directional reflectance model.

TABLE 1: ALBEDO STRATIFIED BY VEGETATION FROM NIMBUS 3 MINIMUM ALBEDO

	TUNDRA	NO. CONIFER FOREST	PRAIRIE/ GRASSLAND	STEPPE/ DRY GRASSLAND	DESERT/ SHRUBLAND	BROADLEAF DECIDUOUS FOREST
			15-30 APRIL 1969 (14-17 APRIL 1963)			
RANGE	50-58* (67-83)*	30-62* (58)*	17-21 (17-19)	17-22	19-23 (19-25)	14-18
AVERAGE	54*	33-38* 14-16 (14)	18	17-18 NORTH 20-22 SOUTH (21-22)	21-22	15-17 (16-17)
			1-15 JULY 1969 (28 JUNE - 3 JULY 1963)			
RANGE	14-27	13-26	16-18	16-21	16-24 (15-25)	14-21
AVERAGE	15-17	13-15	17	16-17 NORTH (14-18) 18-20 SOUTH (17-19)	22 (17)	(14-16)
			3-17 OCTOBER 1969 (5-10 SEPTEMBER 1963)			
RANGE	58* NORTH 19 SOUTH	14-59*	18-36*	52* NORTH 21 SOUTH	18-22 (21-27)	16-23
AVERAGE			21 NORTH (16-18) 18 SOUTH	(19-22)	20	16-18 (14-16)
			21 JANUARY - 3 FEBRUARY 1970 (17 MARCH 1963)			
RANGE	MISSING (60-83)*	36-87* (59-67)*	66* NORTH 19 SOUTH	70* NORTH 22 SOUTH	41* NORTH (17-26)*	45* (20-40)*
AVERAGE			(50-51)* (15-18)	(65)* (19-22)	20 SOUTH 22-23 (19-20)	19 (13-17)

*snow covered surface

() data of Kung et al. (1964)

This is not to say that the differences are due to data reduction but it should be kept in mind that this factor may be as large as the differences noted between the satellite minimum albedo and earlier results. Since minimum albedo appears to be systematically somewhat larger one suspects this to be due to the intermediate atmosphere effect and could qualitatively adjust the data accordingly.

The difference between the two data sets are small. Nimbus 3 data has better spatial integrity on the continental to global scale than any previous work so that it should be considered as comparable with the earlier work of Kung et al. (1964), and as the best to date representation of the earth's surface albedo for other continental areas. Tables 2, 3 and 4 are the same as Table 1 but for other continental areas.

2.3 Diurnal Variation in the Earth Plus Atmosphere Radiation Budget

With the premature failure of GVHRR onboard ATS-6 satellite, a data set from ATS-6 for a diurnal variation study in energy exchange with space is very limited. However, full disk data from VISSR onboard the Synchronous Meteorological Satellite (SMS) now being received at White Sands, New Mexico and archived by Mr. W. Shenk and Dr. F. Hasler at NASA Goddard Space Flight Center - along with sectorized SMS data, will permit continuance of the study.

Techniques and appropriate calibrations for the SMS-VISSR data are under development by the National Environmental Satellite Service (Quarterly Research Report, July-September, 1974) and here at Colorado State University.

TABLE 2: EUROPE

	TUNDRA	CONIFER FOREST	BROADLEAF AND MIXED FOREST	PRAIRIE	STEPPE
			15-30 APRIL 1969		
GROUND	Snow	Snow North	13-20	14-16	15-20 N
RANGE	51-53	13S-45,50N	16-18	15	16 North
AVERAGE	52	----			17-22 S
					21 South
			1-15 JULY, 1969		
RANGE	17-33	14-28	13-18	17-18	16-21
AVERAGE	21-23	14-18	15-17	17-18	21
			3-17 OCTOBER 1969		
GROUND	Snow East	Snow East	Snow NE	17SW-25,30NE	North / South
RANGE	25W-55E	20W-45E	18SW-25,36NE		16-26 / 17-20
AVERAGE	-----	-----	-----		22 / 17-20
			21 JANUARY - 3 FEBRUARY 1970		
GROUND	M	Snow	Snow East	Snow	Snow*
RANGE	M	34-93*	28W to 48-60E	55-69	
AVERAGE	M			61	20 SW tip
					51 E
					67 NE
	--				
		*data incomplete and looks too high and unstable			*except SW tip

TABLE 3: NORTHEAST ASIA

	TUNDRA	CONIFER FOREST	BROADLEAF FOREST	STEPPE	DESERT		
					GOBI	MIDDLE	WEST
			15-30 APRIL 1969				
GROUND	Snow	Snow	18-33	19-30	21-26	26-27	19-25
RANGE	52-54	40-68	20 W	21-23	24	27	23
AVERAGE	53	48	16 E				
			1-15 JULY 1969				
RANGE	15-19	13-20	15-22	15-33	18-31	23-27	18-27
AVERAGE	17	14-16	15-17 W	15-18 W	24	24	22
			21 E	23-25 Central			
				21 E			
			3-17 OCTOBER 1969				
GROUND	Snow	Snow	?	?			
RANGE	57-61	40-65	30-49	20-49	23-39	24-26	21-30
AVERAGE	58	50	38	25-27	27	25	25
			21 JANUARY - 3 FEBRUARY 1970				
GROUND	M	M	Snow	Snow North	Snow		Snow North
RANGE	M	M	50W - 82E	26S - 75N	----	34-38	32S - 68N
AVERAGE	M	M	----	-----	55-60*	36	

*MISSING DATA

TABLE 4: AFRICA

	DESERT		STEPPE	SAVANNAH	TROPICAL RAIN FOR.	THORN FOREST
	N. AFRICA	ARABIA				
			15-30 APRIL 1969			
RANGE	20-40	21-34	15-28 N	15-21	16-25	13-18
AVERAGE	30	27	19-22 N	18	18	16
			11-17 S			
			13 S			
			22-26 Central			
			24 C			
			1-15 JULY 1969			
RANGE	26-38	24-35	18-25	18-25	----	----
AVERAGE	34	30	20	19	----	15
			3-17 OCTOBER 1969			
RANGE	25-42	25-38	----	----	----	----
AVERAGE	34	32	----	17-18	----	16
			21 JANUARY - 3 FEBRUARY 1970			
RANGE	28-43	17-35	----	----	----	18-30
AVERAGE	34	26	----	16-17 N	----	22-23
				22-24 S	----	

A man-computer interactive system called the Optical Data Digitizing and Display System (Fig. 6), within the Atmospheric Science Department at CSU, will digitize SMS film loops and positive transparencies. Power spectrum analysis of digitized time series data from oceanic regions will extract diurnal variations in terms of radiant power from calibrated data and relative change from uncalibrated data.

2.4 Oceanic Precipitation Patterns Using Microwave (ESMR) Data

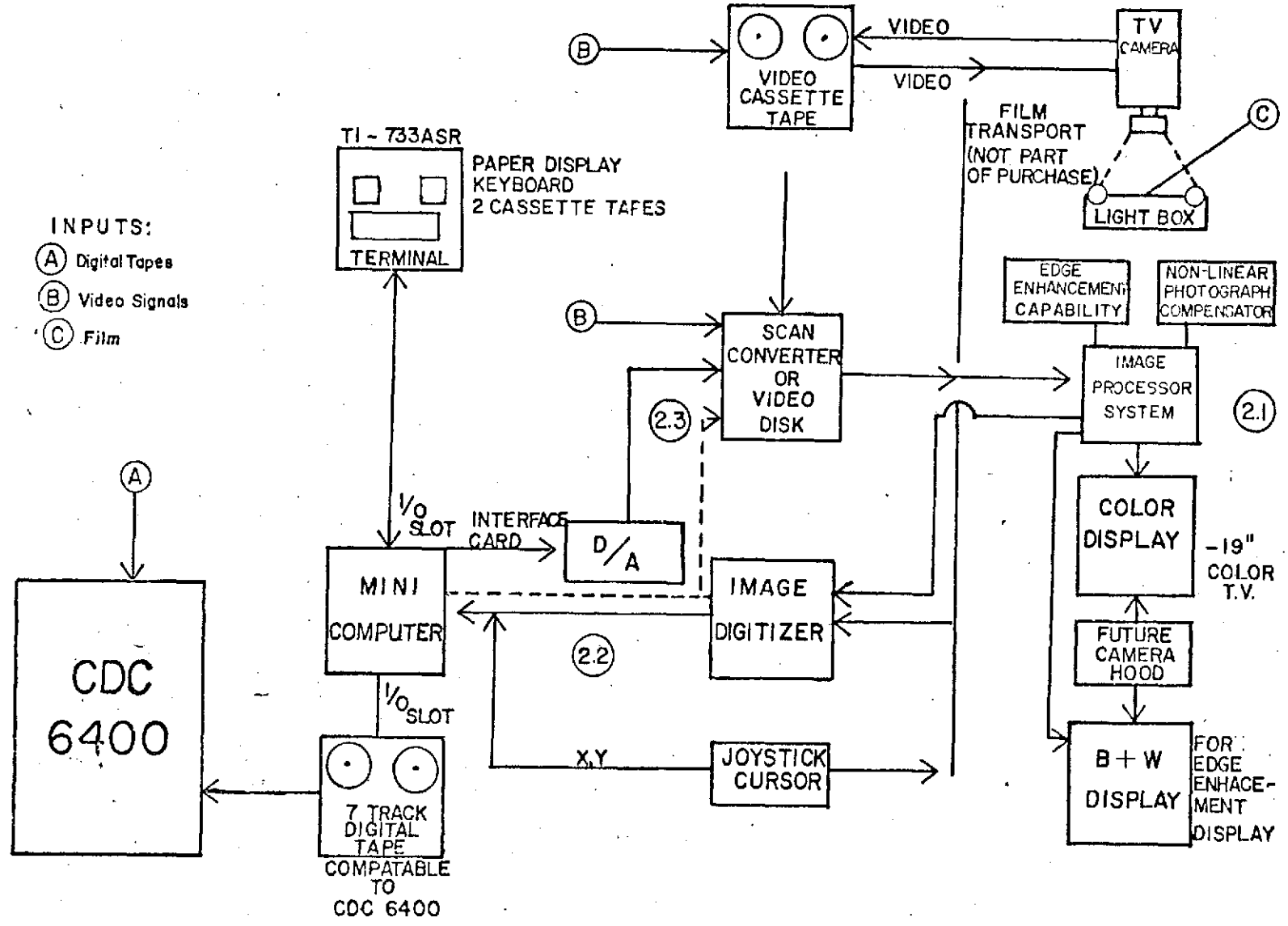
As a first step toward the determination of global latent heat release, microwave data from the Nimbus 5 Electrically Scanning Microwave Radiometer (ESMR) is being used to determine the frequency of occurrence of oceanic precipitation and the diurnal variation of this frequency. In the process a global map of mean 1.55 cm brightness temperature will be calculated for future use as a background. Work on the data for the Winter of 1972-1973 is proceeding and will be completed in the next few months. Data for the Summer of 1973 has been ordered, and analysis should proceed rapidly upon receipt of the data tapes.

During the past year initial investigation was made into the use of concurrent visible, infrared, and microwave satellite data to obtain an accurate estimate of oceanic rainfall rate. The 1.55 cm brightness temperature (proportional to radiance) is a function of rainfall rate (Allison et al., 1974). Although the exact functional relationship is not completely known, it appears that the brightness temperature increases rather rapidly with rainfall rate. An accurate determination of the rain layer itself, then, is essential for accurate determination of the rainfall rate.

Figure 6

(OD^3) OPTICAL DATA DIGITIZER and DISPLAY SYSTEM

COLORADO STATE UNIVERSITY



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There are two problems with using microwave data alone to determine rainfall rate. One is that if the footprint of the radiometer* (approximately 500 km^2 at nadir) is not completely filled with a rain layer, an incorrect mean rainfall rate will be calculated from the mean brightness temperature recorded. It is thought that the high resolution of SMS visible and infrared data could be used to estimate the area of the non-raining portion of the footprint which could be used to correct the mean rainfall rate.

A second problem with using microwave data alone is that the signal is necessarily contaminated by other atmospheric constituents which absorb 1.55 cm radiation - water vapor and clouds being the most important. Although the contamination amounts to only a few degrees Kelvin in the microwave brightness temperature, the error in the rainfall rate would amount to several millimeters per hour. It is thought that a combination of window channel infrared and visible data from SMS could give an estimate of cloud liquid water content which is directly proportional to the microwave brightness temperature error due to clouds. In addition, data from a water vapor channel infrared radiometer such as the 6.7 μm THIR channel aboard Nimbus 5 could give some estimate of atmospheric water vapor, which is directly proportional to microwave brightness temperature error due to vapor (Wilheit, 1972).

In summary, then, the use of visible and infrared satellite data to correct microwave brightness temperature data should yield a significantly more accurate estimate of rainfall rate. Appendix A to this report outlines a plan presented to NASA during the reporting period.

*The Electrically Scanning Microwave Radiometer (ESMR) aboard Nimbus 5

2.5 Bi-Spectral Method to Measure Cloud Parameters from a Satellite

We have a variety of studies underway that use concurrent visible and infrared measurements from high resolution radiation to determine cloud amount and effective temperature. These studies are very closely in line with some also underway by scientists at GSFC. We have had detailed discussions and exchanges of ideas on this topic and plan more work.

3.0 PROGRAM FOR THE NEXT REPORTING PERIOD

A proposal for an extension of grant research was accepted by NASA in September, 1974 for the period through September, 1975. It contains detailed recommendations for a polar energy budget study in addition to continued research as identified during the past grant period, including the cloud determination studies noted above.

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APPENDIX A

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M E M O R A N D U M

October 15, 1974

TO: Bill Nordberg
Bill Bandeen
Ray Wexler
John Theon
Lew Allison
Vince Salomonson
Bob Adler

FROM: Tom Vonder Haar
Stan Kidder

RE: Precipitation Determination from Satellite Data: A Trispectral Approach

This informal memo outlines a potential for expanded research on a topic in which we are all interested. Bill will recall that during the Stockholm meeting on climate, special emphasis was placed on determination of precipitation on a global scale. In addition, for many of our mesoscale applications such as over the ocean as in GATE and over the land for severe weather and hydrology forecasting the precipitation data are in great demand. After using a rainguage, the state of the art is woefully apparent. How can we improve on this state of affairs using satellite data?

Here at CSU our experience with ESMR data (Kidder, Master's thesis, near completion) and separate work using concurrent visible and infrared data (Vonder Haar, 1970; Dittberner and Vonder Haar, 1973; Vonder Haar and Reynolds, 1974) provide the background to suggest a trispectral approach to the precipitation determination problem. Together with your scientists at GSFC we would plan to explore the concept of concurrent visible, infrared, and microwave measurements in order to determine precipitation. The plan is based on the following:

1. Rain comes from clouds, and thus any technique must separate cloud water from rain water.

2. Clouds occur over variable backgrounds; thus any technique must handle the signal-above-background problem.

3. Rain events have different time and space scales; thus measurement sampling and measurement signal-to-noise are affected.

Let's consider the physics of the problem. There are three atmospheric constituents which exist in sufficient quantity to affect the transfer of 1.55 cm microwave radiation. Water vapor has a rotational absorption band centered at 1.35 cm which affects 1.55 cm radiation slightly. Cloud droplets are in the Rayleigh range and absorb slightly. Rain drops, on the other hand, are Mie scatterers and interact strongly with radiation at this wavelength. From Nimbus 5's vantage point, the ocean, which has a low emissivity, appears cold through a cloudy atmosphere. The solution to the equation of transfer for microwaves in a horizontally stratified, plane-parallel atmosphere is

$$T_B = \varepsilon t T_S + \int_o^h T(z)\alpha(z)\sec\theta\, e^{-\int_z^h \alpha(z')\sec\theta\, dz'} dz + (1-\varepsilon)t \int_o^\infty T(z)\alpha(z)\sec\theta\, e^{-\int_o^z \alpha(z')\sec\theta\, dz'} dz \qquad (1)$$

where

T_B = brightness temperature observed from downward-looking microwave radiometer (proportional to radiance)

T_S = surface temperature

ε = surface emissivity

$t = e^{-\int_o^h \alpha(z)\sec\, dz}$ = transmittance from surface to satellite

h = height of satellite

θ = zenith angle of observation

$\alpha = \rho_{cloud} k_{cloud} + \rho_{vapor} k_{vapor}$

$\rho_{cloud,\ vapor}$ = density of cloud, vapor

$k_{cloud,\ vapor}$ = mass absorbtion coefficient of cloud, vapor.

(Westwater, 1972). The first term is the dominant one, but T_B is still small over the ocean in a cloudy atmosphere (~150° K). If a rain layer is present, the above equation no longer applies because rain drops emit and scatter strongly. The result is that for moderate to heavy rainfall rates, no surface radiation at all reaches the satellite. Basically the satellite "sees" the melting level, which has a brightness temperature of 273° K (Allison, et al., 1974). Rain, therefore, appears very bright in comparison with the ocean. Various attempts have been made to correlate brightness temperature with rainfall rate (Allison, et al., 1974), but theoretical and empirical curves do not agree. Several reasons may be responsible for this disagreement, among them failure of the rain area to fill the "footprint" of the radiometer and noise introduced into the system by cloud droplets (as much as 30° K).

We propose to use visible and infrared satellite data to remove some of the noise from the microwave data. The problem of beam-filling can be resolved by the high resolution of the SMS data. And some estimate of cloud noise may be obtained as follows.

$$r = 1.0 - t - a \approx 1.0 - t \tag{2}$$

$$t = e^{-\int k\rho dx} = e^{-\overline{k\rho}x} \tag{3}$$

The solar radiation albedo of a cloud (r) is related to its transmittance which is a function of its liquid water content (ρ), its physical depth (x) (Reynolds and Vonder Haar, 1973), and the optical extinction coefficient (k). In turn, k is wavelength dependent but most sensitive to dropsize distribution (n(r)). Since there are so few raindrops in comparison with the number of cloud drops, and since the smaller cloud drops are much more efficient scatterers of 0.5 μm radiation than raindrops, the product $\overline{k\rho}$ is a measure of the cloud liquid water content, which is proportional to the cloud noise (eq. 1).

There remains the problem of estimating cloud depth (x). In the 11 μm "window" channel, the equation of radiative transfer is

$$N = -\int_o^t B(T)dt + \varepsilon_c t \sigma T_c^4 \tag{4}$$

where

N = observed radiance

B = the planck function

t = transmittance

T_c = cloud top temperature

ε_c = 1 = cloud top emissivity

Some estimate of the atmospheric temperature-height profile allows us to obtain cloud top. Since most of the clouds in a given area have the same base, the 11 μm radiance can provide the cloud depth.

These two additional pieces of information, the 11 μm radiance and the visible albedo, will remove much of the noise from the microwave data and allow an accurate determination of the brightness temperature of the rain layer. Since the brightness temperature of the rain layer rapidly approaches the saturation temperature of 273° K with increasing rainfall rate, it is critical to the precipitation problem that the brightness temperature of the rain layer itself be known accurately, free from cloud droplet contamination.

Summary

The use of passive microwave data to infer precipitation on a global scale is an approach which has a strong first-order physical base. However, we believe that by proper use of concurrent visible and infrared radiometer data we can improve determinations of rainfall rate from the microwave data. Table 1 summarizes this technique. Because of the importance of the precipitation determination problem, the tri-spectral approach should be tested with both measurement and theory.

TABLE 1

Type of Measurement	Physical Relationship to	Use in Tri-spectral Technique
Microwave (1.55 cm)	1. Rainfall Rate 2. Cloud Liquid Water Content	Determine Rainfall Rate
Visible (0.5 μm)	1. Cloud Liquid Water Content 2. Cloud Depth	Remove Contribution of Cloud Droplets to Microwave Data
Infrared (11 μm)	1. Cloud Height	Remove Contribution of Cloud Depth To Visible Data

At CSU we have operating computer programs to calculate the transfer of radiative energy in all three spectral regions under consideration. We believe that satellite and CV-990 measurements over the radar, distrometer, and rainguage network of GATE provide an excellent set of new measurements to use in our research. Several CSU students and staff were on the 990, other aircraft and ships during GATE and we will have firsthand access to the GATE data.

Further expansion of the line of inquiry proposed here would involve an "amalgamated" approach using additional satellite data (i.e., sounder and 6.7 μm channel) to improve the cloud level specification. However, we think the tri-spectral approach should be studied in detail at the present time.

References

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Appendix B:

Cummulative Summary of Reports and Papers Under Grant NGR-06-002-102

1. A preliminary report on heat budget measurements from Nimbus-III was partly supported by this grant. It was presented at the XIIIth Meeting of COSPAR, Leningrad, 1970, and was published in Space Research XI (Springer-Verlag) as:

 The radiation balance of the earth-atmosphere during June and July 1969 from NIMBUS-III radiation measurements--some preliminary results

 by

 E. Raschke, T. Vonder Haar, W. Bandeen, and M. Pasternak

2. The very early results of four seasons of Nimbus radiation data were compared to earlier results from other satellites, with METEOR data obtained during the same time period and with calculations in a paper presented at the January 1971 Annual Meeting of the American Meteorological Society:

 Global measurements of the energy exchange between earth and space during the 1960's, including latest results from the NIMBUS-III satellite

 by

 T. Vonder Haar, E. Raschke, M. Pasternak, and W. Bandeen

 Publication of these comparisons awaited analysis of a more complete Nimbus data set (see #7).

3. In March 1971 the author presented an invited paper at the Miami Remote Sensing Workshop:

 Global radiation budget and cloud cover by satellite measurements

 by

 T. Vonder Haar

In addition, he served as discussion leader of a section that considered present opportunities and future possibilities for parameterizing the atmospheric energy budget using satellite data. Proceedings of this workshop will be published.

4. An invited paper was presented at the International Solar Energy Society Conference, NASA, GSFC, in May, 1971. This paper presents results of special interest to scientists concerned with the measurements and use of solar radiation. It was published in Solar Energy Volume 14, no. 2, 1972.

Measurements of solar energy reflected by the earth and atmosphere, from meteorological satellites

by

T. Vonder Haar, E. Raschke, W. Bandeen and M. Pasternak

5. At the XIVth meeting of COSPAR (Seattle, 1971), in an open meeting of Working Group 6, we formally presented the annual results of the earth's radiation budget measurements from NIMBUS-III. They independently confirmed global results obtained from earlier satellites, while providing the first high area resolution view of energy exchange between earth and space on the annual scale. The paper, was published in Space Research Vol. 12, 1972 and is entitled:

The radiation budget of the earth-atmosphere system as measured from the NIMBUS-III satellite (1969-70)

by

T. Vonder Haar, E. Raschke, M. Pasternak and W. Bandeen

6. Drs. Budyko and Flohn kindly invited a paper on the NIMBUS-III results for their Symposium on Physical and Dynamical Climatology, Leningrad, August 1971. The paper, read in the authors absence by Dr. A. Drummond will be published in the symposium proceedings. It was titled:

Climatological studies of the earth's radiation budget and its variability with measurements of the satellite NIMBUS-III

by

E. Raschke and T. Vonder Haar

7. An invited paper at the Joint Meeting of the German Physical and Meteorological Societies, Essen, October 1971 contained a discussion of the new NIMBUS results within the framework of the earlier satellite measurements, especially with regard to interannual variations. It was published in a German journal, Amalen Meteor, 6 - No. 711, 1973.

Measurements of the energy exchange between earth and space during the 1969's from satellites

by

T. Vonder Haar and E. Raschke

8. In addition to the formal papers and publications, one of the most personally satisfying events of the reporting period was a 90-minute seminar presented in early November 1971 in the invited seminar series of the Geophysical Fluid Dynamics Laboratory, NOAA/Princeton University. Entitled: Measurements of the Earth's radiation budget from satellites: Status, prospects and relation to atmospheric energetics, the seminar reiterated both the wide-ranging relevance of radiation budget data to many atmospheric problems as well as the interest of other scientists in these data. This same experience has greeted the author during similar seminars presented in recent years at MIT, NYU, University of Colorado, and Colorado State University.

9. Invited paper at the International Radiation Symposium, Sendai, Japan, May - June 1972 and also presented at the Conference on Atmospheric Radiation, Fort Collins, Colorado, August 1972. Paper discusses variations in the Radiation Budget as measured by satellites at various

spatial and temporal scales i.e. spatial scales: global, hemispherical, zonal, regional, ocean-land; and time scales: hourly, daily, monthly, and yearly.

Natural variation of the radiation budget of the earth-atmosphere system as measured from satellites

by

T. Vonder Haar

10. A paper was presented at the Conference on Atmospheric Radiation, Fort Collins, Colorado, August 1972 which discusses an experiment to measure the radiation budget at the surface over a snow field and its variation with changing solar Zenith angles and cloudiness. This information is needed to understand the total heat budget of polar areas which is vital to understanding our climate changes.

The albedo of snow in relation to sun position

by

H. Korff and T. Vonder Haar

11. Measurements of the earth's radiation budget from satellites were combined with atmospheric energy transport summaries to show the required transport by the oceans between equator to pole. The results show that the ocean must transport more energy than previously believed, a timely result, since there is a renewed interest in the influence of the ocean on weather and climate. Published Journal of Physical Oceanography April 1973.

New estimate of annual poleward energy transport by Northern Hemisphere oceans

by

T. Vonder Haar and A. Oort

12. The frequency and occurance of opaque cloudiness were determined from satellite brightness data. Opaque cloudiness interferes with remote sensing of the vertical temperature profile of the atmosphere. The study indicated regions of the globe where remote temperature sounding at spectral regions less than microwave bands are not feasible due to persistent opaque cloudiness - necessary information for the Global Atmospheric Research Program (GARP) planning.

A study of extreme and persistent cloudiness based on satellite observations (1969-1970)

by

P. Downey, S. Lassman, and T. Vonder Haar

13. Nimbus III MRIR data were combined with surface albedo and actinometric measurements to determine the temporal (15 day to year) and spantial (regional to global) distribution of atmospheric absorption of solar energy. In addition a statistical parameterization relating atmospheric absorption to precipitable water, opaque cloud cover, and satellite measured albedo was developed.

Distribution and parameterization of absorption of solar radiation in the atmosphere

by

P. Downey (M.S. thesis)

14. Satellite measurements of the earth-atmosphere radiation budget components, comprising 36 monthly data sets, were used to compute the north-to-south net radiation gradient - the forcing function for the large scale atmospheric and oceanic circulation. These data, when compared to atmospheric circulation parameters, indicate that year-to-year anomalies in the large scale atmospheric circulation lag the year to year anomalies in the gradient of net radiation by 3 to 6 months.

Interannual variations in the earth's radiative budget and the general circulation

by

J. Ellis, (M.S. Thesis)

15. Invited paper presented to a joint session of the Radiometry and Photometry and Atmospheric Optics Technical Groups, 1973 Meeting of the Optical Society of America, Denver, Colorado discussed the precision and accuracy required of radiometric measurements by satellites at various time and space scales-particularily, the global climate change and its measurement problems.

Global heat balance

by

T. Vonder Haar

16. Invited paper at the 1973 National Center for Atmospheric Research (NCAR) Summer Climate Meeting, Boulder, Colorado, a national collection of scientists involved in climate research. The capability for measurements from satellites of the initial and boundary conditions for inclusion into global climate models was assessed. Satellite measurements to date show that the short term climate (year to decade) is not stagnant.

Satellite observations of the earth's energy budget

by

T. Vonder Haar

17. In a paper presented at the Interdisciplinary Symposium on the study of Snow and Ice Resources, Monterey, California, December 1973, the data reduction technique applied to Nimbus III measurements for albedo and the need for additional surface measurements of bidirectional

reflectance characteristics of ice and snow surfaces were discussed.

Measurement of albedo over polar snow and ice fields using Nimbus-3 satellite data.

by

T. Vonder Haar

18. Invited paper at the Smithsonian Symposium on Solar Radiation Measurement and Instrumentation, Rockville, Md., November 1973, in which results of measurements with different experiments of the solar energy reflected and scattered from the earth-atmosphere were presented. The application of these measurements to several environmental problems was reviewed and new experiments designed to obtain future albedo measurements were noted.

Measurement of the Planetary Albedo from Satellites

by

T. Vonder Haar

19. NASA Technical Note D-7249, April 1973, discusses the complete radiation budget experiment using data from the MRIR on Nimbus 3, the extensive data reduction method (including assumptions) and results for four semi-monthly measurements periods (May 1-15, 1969; July 16-31, 1969; October 3-17, 1969; and January 21 - February 3, 1970).

The radiation balance of the earth-atmosphere system from Nimbus-3 radiation measurements

by

E. Raschke, T. Vonder Haar, M. Pasternak, and W. Bandeen

20. Measurements of reflected solar radiation and emitted thermal radiation taken with the MRIR on Nimbus-3 satellite are presented for the 10 semi-monthly periods spanning April 1, 1969 to February 3, 1970. Results on the planetary albedo, the amount of absorbed solar radiation, the infrared radiation loss to space, and the radiation balance

of the earth-atmosphere system are discussed at various scales: global, hemispherical, and zonal averages as well annual polar and global maps.

The annual radiation balance of the earth-atmosphere system during 1969-70 from Nimbus 3 measurements.

by

E. Raschke, T. Vonder Haar, W. Bandeen, and M. Pasternak

21. Invited paper at the 1st IAMAP Special Assembly, Symposium on Clouds and Radiation, Melbourne, Australia, January, 1974. Paper presented ways in which the vertical distribution of cloudiness would influence the equator-to-pole net radiation gradient. Interpretation of the year-to-year differences included discussion of non-reciprocity of planetary albedo and infrared exitance arising from varying cloud fields.

Satellite Measurements of the Interannual Variations of the Equator-to-Pole Radiation Gradient, the Effect of Clouds and the Response of the Large-Scale Circulation

by

T. Vonder Haar and J. Ellis

22. Presented at the Climate Project Meeting, NCAR, September 16-18, 1974. Using satellite determined albedoes rather than Budyko's and a parameterization between infrared exitance to space and solar absorption, the seventeen season satellite data showed the climate model to be more stable to changes in solar constant than did Budyko's earlier work. However, the parameterization in both models seems quite inadequate.

Analysis of the Leith-Budyko Climate Model Using 17 Season's Satellite Radiation Budget Data

BY

J. Ellis and T. Vonder Haar